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Published in:
Journal of Cleaner Production

DOI:
10.1016/j.jclepro.2022.135379

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Ramos, T. M., Christensen, T. B., Oturai, N. G., & Syberg, K. (2023). Reducing plastic in the operating theatre: Towards a more circular economy for medical products and packaging. *Journal of Cleaner Production*, *383*, [135379]. https://doi.org/10.1016/j.jclepro.2022.135379

Journal of Cleaner Production 383 (2023) 135379

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Reducing plastic in the operating theatre: Towards a more circular economy for medical products and packaging

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ARTICLE INFO

Handling Editor: Govindan Kannan

Keywords:
Circular economy
Single-use devices (SUDs)
Medical plastics
Recycling

ABSTRACT

Plastic single-use devices (SUDs) are favoured by healthcare facilities, especially surgical departments, for their convenience, sterility, and single-use quality assurance. Medical facilities are responsible for generating large amounts of CO_2 emissions due to resource-intensive processes and reliance on single-use plastic products, among other factors. Currently, there are knowledge gaps in literature about specific types and amounts of plastic products generated by hospitals, and more specifically, operating theatres. Existing relevant research focuses mostly on waste management solutions, negating the potential solutions further up the value chain. While considerations that focus on waste management and end-of-life are important, those that span the rest of the value chain, including the circular economy and the waste hierarchy, are inherently important. This study addresses this knowledge gap by quantifying these fractions and making recommendations to reduce them. Observations, polymer analysis, and surveys with medical staff were conducted at two hospitals in Denmark. Results suggest that the current design of medical products and packaging does not consider the end-of-life fate of the product, making current sorting and recycling options impossible. Recommendations from this study highlight external responsibilities such as those of producers and manufacturers to include consideration of the end-of-life fate of the product within the design phase. These are in addition to internal responsibilities such as the use and sorting of these fractions.

1. Introduction

The design of many medical plastic products on the market today is created with considerations of cost and convenience but not of end-of-life fates such as sorting or recycling. Plastic products and applications have become ubiquitous across all sectors and it is estimated that greenhouse gas emissions from plastics will reach 1.34 gigatons per year by 2030 and 2.8 gigatons per year by 2050 (Shen et al., 2020). Individually wrapped single-use plastic devices (SUDs) continue to contribute to a well-established history of performance and safety, specifically within medical products (Romeo, 2020). The healthcare sector is responsible for roughly 4.6 percent of global greenhouse gas emissions as a result of resource-intensive facilities and, indirectly, the supply chain of medical products and procedures (Beloeil and Albala-dejo, 2021; MacNeill et al., 2020). While there are several studies that have focused on global greenhouse gas emissions generated by the healthcare sector (Eckelman et al., 2020; Lenzen et al., 2020; Rasheed et al., 2021) and waste management recommendations (Fletcher et al., 2021; Lee et al., 2002; Patrício Silva et al., 2020), few publications focus on the production and use phases of plastic (Johansen et al., 2022). Knowledge gaps include what specific types and amounts of plastic medical products are being used (what types of polymer). While this study does not gather data across the production phase of the value chain, recommendations for each phase within the value chain are considered.

With an increased awareness of the harmful environmental effects of plastics, regulation within the EU has started to promote the reduction of carbon emissions and increased recycling of plastic products. When considering medical waste specifically, the Waste Framework Directive is a legislation that highlights plastic waste prevention as a priority (Wilts and Bakas, 2019). By introducing the 'waste hierarchy', the directive targets reduction as the primary method of waste prevention, followed by reuse, recycling and recovering before the least optimal method, which is disposal – popularly referred to as the four Rs (Ololade and Orimoloye, 2022). The directive and waste hierarchy were both very much taken on board throughout this study.

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https://doi.org/10.1016/j.jclepro.2022.135379
Received 20 April 2022; Received in revised form 18 November 2022; Accepted 25 November 2022
Available online 6 December 2022

Increasing amounts of plastic waste are a consequence of an increase of SUDs and the current linear value chain of plastic products in which products are produced, transported, used, and then disposed of thereafter (MacNeill et al., 2020). To combat this wasteful model, the circular economy (CE) model was developed (Kirchherr et al., 2017; Stahel, 2019) and widely adopted in academia as a framework for understanding waste flows in the economy (Christensen and Hauggaard-Nielsen, 2020; Ghisellini et al., 2016), in policy as a framework for waste, resources and product policies (European Commission, 2020; McDowall et al., 2017), and in industry as a framework for resource productivity and eco-design (Bocken et al., 2016; Geissdoerfer et al., 2018). A transition to a more circular value chain requires that products are designed to be remade, reused, reprocessed, and remanufactured in efforts to keep products and materials within the value chain (Ellen MacArthur Foundation, 2013; MacNeill et al., 2020).

The continuous impacts of the current 'take-make-waste' model of SUDs is becoming evident – few changes have been made to mitigate these harmful effects and the persistent use of SUDs (MacNeill et al., 2020). Circularity of products within the medical sector faces an extra level of scrutiny as the challenge of sterility and safety are emphasized when considering reuse of medical tools (Kane et al., 2018). While not all plastics in healthcare can be avoided, prioritization on reducing them and replacing a few key product categories can reduce healthcare plastic consumption significantly (Gamba et al., 2021). A critical aspect is the consideration of reverse logistics in terms of providing material flows backwards in the supply chain and for SUDs, from end-of-life back to the origin (Zarbakhshnia et al., 2022).

SUDs and plastic-packaging supply systems are inherently different according to sector, and demand in-depth, multi-approach perspectives to change direction towards a circular economy. A recent systematic literature review by Meherishi et al. (2019) further underlines the urgency for industry-specific studies that not only account for the material flows throughout the supply chain, but also consider the involved stakeholders' roles, collaborative approaches, and incentives.

To assess the various aspects of healthcare plastics, mixed method approaches are relevant for complex systems and take both qualitative and quantitative data into account to be able to explore healthcare trends and practices in depth (Shorten and Smith, 2017). The novelty of this study is that it focuses on a mixed methods approach where data was gathered to provide site-specific recommendations that consider the circularity of these plastic products across the value chain, while including the expert opinions and first-hand experience of the staff.

This study aims to analyse how single-use plastic consumption can be reduced in operating theatres, with two Danish hospitals (Næstved Hospital and Slagelse Hospital, Region Zealand) as case studies. With the use of a mixed methods approach, observations of plastic consumption in the operating theatre (OT) were included as well as staff surveys, allowing for both quantification of plastic consumption and assessment barriers for reducing these fractions. Relevant studies within Danish healthcare facilities are scarce.

2. Material and methods

2.1. The case area

Denmark is composed of five regions (North Denmark Region, Central Denmark Region, Region of Southern Denmark, the Capital Region of Denmark, and Region Zealand). This study was conducted in two hospitals (Slagelse Hospital and Næstved Hospital) within Region Zealand. Region Zealand contains seven general hospitals and one psychiatric hospital. In 2010 the Danish Regional Council divided the seven general hospitals, which means that Slagelse Hospital is considered an emergency hospital, while Næstved Hospital is seen as a specialist hospital (Region Zealand, 2015). Slagelse Hospital has four main surgical departments including gynaecology, orthopaedics, gastroenterology, and urology, among others, with a total of 15 operating theatres. Næstved Hospital has two surgical departments: urology and orthopaedics, and is known for being the second largest centre in Denmark for surgical replacements such as hips and knees, with a total of 10 operating theatres. (Region Zealand, 2015).

2.2. Methodological approach

In order to analyse how plastic consumption in the hospital sector can be reduced, we conducted a systematic four-step analysis based on a parallel mixed method approach in which quantitative and qualitative data were collected concurrently (Shorten and Smith, 2017). The four steps were i) preliminary screening and category implementation, ii) analyses of plastic flow in operating theatres, iii) post-use analysis of relevant products, and iv) surveys targeting key staff (Fig. 1).

2.3. Preliminary screening and category implementation

To reduce plastic waste generated and disposed of in the operating theatres of Slagelse and Næstved, an assessment of products, product types, and use was needed. The operating theatres were specifically chosen, as opposed to other areas/departments within the hospitals, based on a previous preliminary screening of plastic material flow within a hospital conducted by an engineering consultancy (unpublished data). The screening included pilot projects that focused on plastic within a hospital from 1) food containers, 2) plastic foil, 3) cleaning solution bottles, and 4) mixed plastic fractions from the operating theatres. The screening concluded that the most significant reductions could be achieved in the operating theatres and further highlighted a knowledge gap pertaining to the types and amounts of plastic from operating theatres. This specific knowledge gap highlighted in the external screening served the basis for this study.

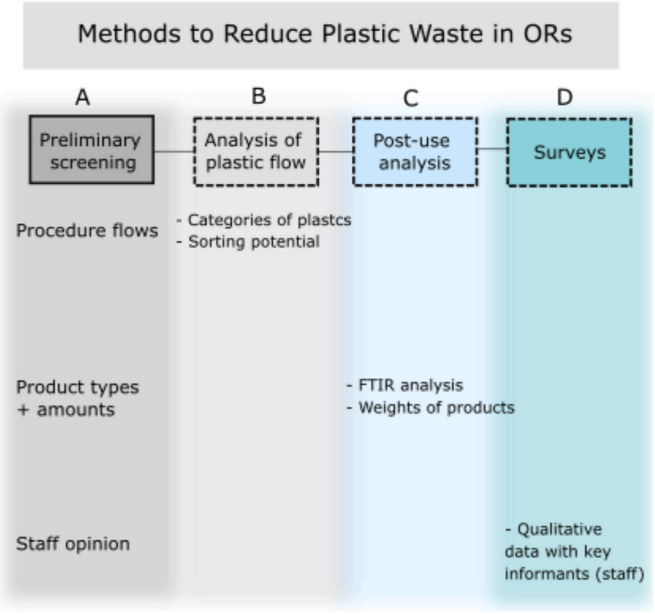


Fig. 1. A mixed method analysis was chosen to look at the various aspects of product type, procedural flows, and the opinion/expertise of the staff. A) A preliminary screening was conducted where the Assessment Capacities Project (ACAPS) Direct Observation and Key Informant Interview Techniques for primary data collection during rapid assessment was considered as a basis for the direct observations of rapid procedural flows. B) A detailed list of plastic product types and specific amounts was highlighted by the preliminary screening and literature review. C) Infrared spectroscopy was conducted to assess products' polymer types and the corresponding weight of each product. D) Voluntary key informant surveys were provided to staff at both hospitals to take into account their expert opinions.

To create a systematic approach to rapid data collection, categories of relevant plastics were created to act as a checklist during assessments (ACAPS, 2011). Based on material flows observed during our preliminary screening of Slagelse and Næstved, seven plastic categories were created: syringes, caps, composite soft packaging, composite hard packaging, blue sheets, soft plastic, and hard plastic. During the assessment, once a product or package was opened for use it was recorded under the appropriate category to quantify the amounts of these fractions. Items were only included for categorization if they were opened exclusively in the OT, to check for additional plastic that may be included in the packaging of the product. As in most operating theatres, there were adjacent prep rooms where doctors and nurses would dress in sterile gowns and gloves and then come into the OT ready to operate. Gloves were therefore excluded from the categories, as they could have been accessed outside the operating theatres as well as inside, and the potential additional plastic associated with the glove packaging (if opened in the prep room) could not be directly seen. Assumptions of products were not made unless the opening and disposal of the products were directly observed in the OT.

2.4. In-depth analyses of plastic flow in operating theatres

Direct non-participant observations (Ciesielska et al., 2017) of plastic use and plastic waste generation were carried out in OTs at two hospitals. The observations served two main objectives: 1) to record and categorize plastic waste produced during operations and 2) to identify workflows and procedures (formal as well as informal) at the OT associated with plastic management, use, and waste generation.

The observations were carried out from February 2021 to June 2021 for Slagelse Hospital and from March 2021 to May 2021 for Næstved Hospital. Observations were conducted in the surgical departments of both hospitals in accordance with the scheduling/planning of the hospital staff. In total, 31 operations were observed at Slagelse and 15 operations were observed at Næstved. Data generation primarily consisted of direct observations of the staff's day-to-day processes within the OT recorded in field notes, as well as counting plastic products and packaging used. The use of field notes during direct observations includes a multifaceted approach widely used to capture intricate and complex processes, such as medical plastic product flows (Andreassen et al., 2020).

The field notes focused on the relation between surgical activities and plastic use (including plastic handling and waste generation). The observations contributed additional information such as differences among surgical departments, between the two hospitals, types and amounts of plastic waste in the operating theatres, as well as staff procedure.

The working flow during operations was split into three phases. Phase 1:, pre-operation, including the preparation, Phase 2: operation, including all the activities needed to perform and conduct the actual operation, and Phase 3, post-operation procedures including cleaning. This differentiation serves as a basis for the discussion on implications for redesign, reuse, reduction, and recycling opportunities during the analysis part of the paper.

2.5. Post-use analysis of plastic products

To analyse polymer types, attenuated total reflection Fourier transform infrared (ATR-FTIR) spectroscopy was used. A single bounce diamond internal reflectance element (2 × 2 mm) was utilized to run scans at a resolution of 2 cm^{-1} between 4000 and 650 cm^{-1} using a PerkinElmer Spectrum Two spectrometer. Samples were cut into 1 × 1 cm squares which were then sampled on both sides. Additionally, multiple analyses were conducted per sample on differing locations on the sample to ensure an accurate representation of polymers, especially with composite products. Polymer characterization was based on at least a 90% match with reference spectra as well as manual assessment of compliance with peaks within the 1400–4000 cm^{-1} range of the spectra (Syberg et al., 2020).

Relevant samples of products identified during the observation were collected from the storage depots, anaesthesia trolley, or operating theatre waste bins. Products included in surgical kits were therefore not chosen for analysis due to lack of post-use availability. A list of products and packaging with respective polymers can be found in Table 1.

The products were further individually weighed using a Sartorius analytical lab scale with a range of 20 mg–200 g, as well as a digital scale with a range of 2–5000 g. Individual weights of products and the average amount of products used per operation were used to calculate the overall weights per operation within the respective categories of products.

2.6. Surveys targeting key staff

A survey was distributed to staff at both hospitals after the observations were complete (see supplementary data). The surveys were concise and included questions to gauge the staff's overall level of engagement as well as to consider their first-hand experience with the plastic products, following recommendations found in the technical brief by ACAPS, Direct Observation and Key Informant Interview Techniques for primary data collection during rapid assessments. The total amount of surveys, including distribution of answered surveys across staff, can be seen in Fig. 2.

The surveys consisted of six main questions with sub-questions that focused on staff opinions on reducing the amounts of plastic being used. The questionnaire was presented optionally both in Danish and English, and the staff were encouraged to answer in the language with which they felt most comfortable. The participants were informed that their identity would remain anonymous, in accordance with the GDPR

Table 1
Results from the FTIR polymer analysis. This analysis was conducted on products that were readily available for post-use analysis, therefore items in surgery kits were not included. Additionally, the 'composite hard' category was also excluded for the same reason. If a product contained more than three polymers, they were noted as mixed polymer with the corresponding number of identified polymers in parenthesis. The products included in the table below represent the most used products throughout all departments.

Categories	Products	Polymer type
Syringes	1: 50 ml	**1:** PP
	2: 20 ml	**2:** PP
	3: 5 ml	**3:** PP
Caps	**1:** Syringe cap	**1:** PP
Composite (soft)	1: Syringe packages (plastic only)	1: PE, nylon
	2: Proset Intrafix IV tubes	2: PCT, PE
	3: Laryngeal tube	3: EVA, nylon
	4: Cap + needle package	4: PP, PE
	5: Sterile centre composite (green tint)	5: PP, PET
Blue sheets	1: Haylard	1: PP
	2: Evercare surgical sheets	2: PE, PP, PET
	3: Surgical gowns	3: PET
	4: Blue gauze cover	4: PP
Soft plastic	1: Gas mask wrapper	1: PE
	2: Nasal cannula	2: Mixed polymer (5)
	3: Nasal cannula wrapper	3: PE
	4: Suction tube wrapper	4: PE
	5: Proset Intrafix IV tubes	5: Mixed polymer (5)
	6: Biogel Indicator glove wrapper	6: PCT, PE
	7: Surgical gown wrapper	7: PE, nylon
	8: Tool holder	8: PE
	9: NaCl 3000 bag/soft package	9: PVC, PE
	10: Oxygen tube package	10: PP
Hard plastic	1: Gas face mask	1: PVC, PC
	2: Suction tubes	2: PBT
	3: Laryngeal tube/hard cover	3: Multi-polymer (3)
	4: Sharps box	4: Multi-polymer (3)
	5: Mini-Spike	5: PE
	6: Oxygen tubes	6: PP

Table 2
Further emphasizes the potential implications of this study which gathers four specific recommendations across the value chain of plastic medical products that the Region of Zealand should consider, along with the current barriers to each.

Suggested implementations across the value chain	Production	Use	End-of-life
1. Production and procurement of sustainable medical products	Medical products should be designed in a manner that considers the fate of products at the end-of-life phase. Currently, many multi-polymer and composite material tools make recycling options impossible.	The use of alternative materials such as glass and metals as well as single-polymer products or easily disassembled composite material products can ensure easier on-site sorting. Current procurement seems to favour plastic SUDs.	Products should be kept in the value chain after use for as long as possible by means of sterilization, refurbishing or recycling. Single-use plastic products should be avoided where possible.
2. Slight procedural changes to ensure on- site sorting		Healthcare workers should be able to easily separate and/or sort fractions of high-quality plastic for recycling or return/store items for sterilization.	
3. Recycling of clean/ uncontaminated fractions of plastic		Plastic medical waste that has not been in contact with patients should be considered for recycling instead of the current method of disposal.	Specific polymers should be agreed upon by waste handlers to be collected and recycled.
4. Consider switching from selected single-use products to comparable multiple-use products	Procurement should consider multiple-use alternatives to single-use plastic products.	Slight procedural changes should incorporate the handling and storing of multiple-use products	The addition of more multi-use medical products should be considered, minimizing waste generation.

(Blackmer, 2018).

3. Results and discussion

3.1. Direct observations

Direct observations at both hospitals provided insights into the amount and types of plastics being used, as well as procedural flows to assist with potential sorting implementations. Fig. 3 shows the overall average amount of plastic types used per operation at each hospital. At both hospitals, composite soft packaging is the most abundant (38% and 26% for Slagelse and Næstved, respectively), while syringe caps (4% and 3% for Slagelse and Næstved, respectively) and composite hard packaging (3% at both hospitals) are the least used items per operation.

There are noticeable differences between soft plastic (18% and 25% for Slagelse and Næstved, respectively) and hard plastic usage (16% and 22%, respectively) between the hospitals. It was noted that these differences in use of products may be attributed to the types of surgery performed. For each surgical department there are different tools,

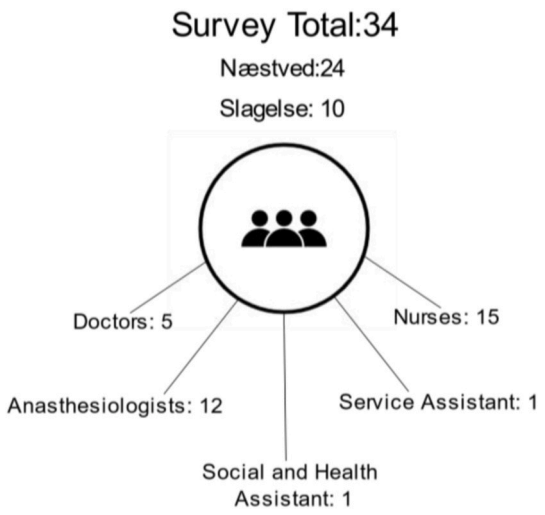


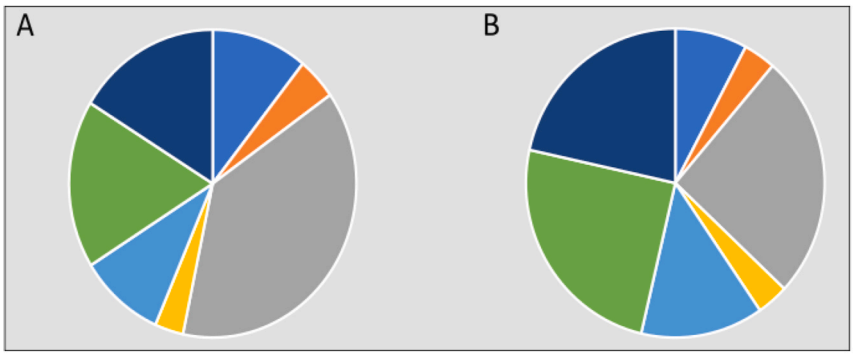
Fig. 2. The total number of completed surveys, as well as the number of surveys completed per hospital. The breakdown of responses per occupation is also shown. Most responses were provided by the nurses or anaesthesiologists in the surgical departments who, based on observations, are the staff members who come into direct contact with the majority of the plastic medical devices.

products, and procedures, so surgical departments differ slightly in their composition of plastic medical waste produced. While it is not feasible to eliminate all medical plastics, focusing on few products with high consumption value may lead to considerable progress in reducing plastic consumption in the healthcare sector (Gamba et al., 2021).

Slagelse and Næstved both have urology and orthopaedic departments; Fig. 4 illustrates the amounts of products used per operation within these departments for both hospitals.

Quantification of plastic medical packaging through procurement data alone is extremely difficult; however, up to 50% of total plastic waste can consist of plastic packaging, which emphasizes the need for prioritization of reduction efforts (Circle Economy and Nederlands Circulair, 2015; Gamba et al., 2021). The most used products in Slagelse and Næstved are composite (soft) packages. An average of 30 composite packages are used per operation, typically composed of paper and plastic, designed for steam sterilization. Medical packaging, such as these composites, helps preserve the sterility of surgical instruments before use by preventing microbial contamination from the external environment after the sterilization process (Klumdeth et al., 2020). These composites encase individually wrapped and sterile single-use products from producers and manufacturers, but also reusable metal instruments from the hospitals' sterilization departments.

On-site separation of composite packages into plastic and paper could markedly increase the recycling potential. However, the current amounts and product design of these composite packages is not conducive to on-site sorting. Medical staff surveys revealed that the adhesive that binds the paper and plastic portions together is rather difficult to separate, making it practically impossible to implement this additional waste-sorting step. Possible solutions to this dilemma must therefore be found earlier in the value chain, for instance in product design. This could be either with a change in the adhesive used for the current product, or a shift in procurement to a reuse product such as a reusable sterilization pouch, for example the FDA-approved Enviropouch which can be used a minimum of 200 times (Enviropak, 2021). Considerations such as these that include thinking about the entire life cycle of a product, including product design, are becoming inherently important as they have the potential to minimize the use of raw materials and should include possibilities for the end-of-life phase, contributing to the circular economy perspective. Additionally, reusable pouches such as these should not hinder the workflows of staff that use them, aside from sorting reusable pouches from waste. A life-cycle



	Syringes	Caps	Comosite Soft	Composite Hard	Blue Sheets	Soft Plastic	Hard Plastic
(A) Slagelse	11%	4%	38%	3%	10%	18%	16%
(B) Næstved	8%	3%	26%	3%	13%	25%	22%

Fig. 3. Percentages of plastic products, within the respective categories, from both Slagelse (left) and Næstved (right), per operation. The largest fraction of waste within both hospitals comes from soft composite packaging, which is used to encase individually wrapped medical tools.

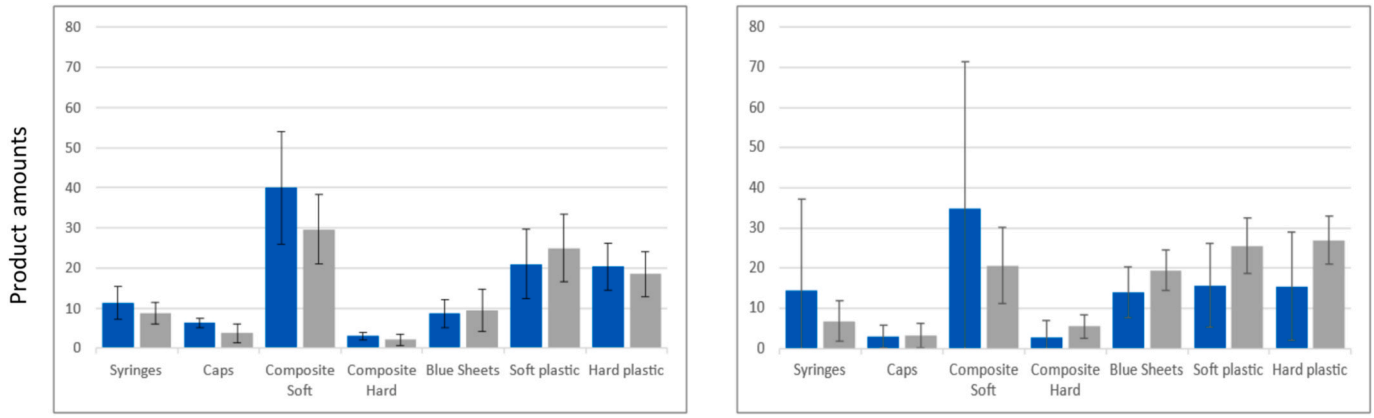


Fig. 4. Total amount of plastic waste per operation in the urology and orthopaedic departments at Slagelse Hospital (blue) and Næstved Hospital (grey). Composite soft packaging remains prevalent at both hospitals, but overall use is slightly higher in their urology departments.

assessment (LCA) of single-use composite packaging and a reusable alternative should be conducted to further analyse the environmental impacts of both products.

Aside from composite package use, additional differences between the departments exist in the use of blue sheets, hard plastic and soft plastic; the differences between the hospitals are discussed below.

Næstved.

As mentioned, Næstved is considered a specialist hospital, specializing in orthopaedic prosthetics/implants. These specific procedures require an additional level of sterility compared to other orthopaedic surgeries to avoid surgical site infection (Al-Mayahi et al., 2015). As a result, the use of surgical drapes (included in the 'blue sheet' category) is most prevalent in the Næstved orthopaedic department. Other products included in the blue sheet category include surgical gowns worn by the staff, which are individually encased in soft plastic, as well as single-use Haylard sterile sheets, as these products are typically non-woven PE (Gamba et al., 2021). In addition to the Haylard sterilization wraps, reusable steel containers were also occasionally used to transport sterilized medical tools from the sterilization department and thus did not occupy copious amounts of space in operating theatre waste bins.

Reusable steel sterilization cases offer the convenience of sterility with the advantage of reusability, as opposed to the single-use Haylard sheets that can be perforated (Van Gorp and Starcovic, 2017). Switching over entirely to steel sterilization containers may not be feasible for all hospitals, due to lack of storage space, lack of resources for sterilization departments, and associated costs – introducing a few reusable cases, when possible, to supplement some of the single-use sterile sheets could be a feasible scenario for hospitals. Additionally, Haylard offers a buy-back system in which their customers can return used sterile sheets to the production facilities to make new sterile blue sheets, which is another path towards reduced consumption (Haylard, & O&M, 2022).

Fig. 4 further illustrates an increased use of 'soft plastics' and 'hard plastics' in the Næstved orthopaedic department, compared to the Slagelses orthopaedic department. A single operation typically requires several single-use plastic products, including the use of at least four 1-L bottles of water/NaCl and at least six polypropylene plastic bowls and trays in varying sizes. Most of the single-use plastic products used in these prosthetic/implant operations come from the surgical kits to ensure that needed equipment is transferred to the operating theatre within a single kit for each surgery. These kits and their contents differ drastically depending on surgeon, operating theatre, and surgery type and often contain a large quantity of plastic products. As mentioned,

these plastic products include packaging as well as tubing, bowls, and trays, and many other single-use plastics. Considerations towards the replacement of these single-use products with multi-use materials can reduce the overall amount of plastic consumption within healthcare facilities (Gamba et al., 2021). For example, it was observed that both metal and single-use scalpels and bowls were used interchangeably. If the reusable option can perform equally, it is worth considering as a replacement for single-use products. Even though the price of individual products might be more expensive, changing to multiple-use alternatives can also potentially aid in saving the procurement departments money spent on constant restocking of single-use items (North and Halden, 2013).

It is estimated that less than 10% of all plastics produced have been recycled, and considering the complexity of healthcare plastics, recycling within healthcare facilities can potentially be lower (Gamba et al., 2021; Geyer et al., 2017). Recycling can be limited due to difficulties with sorting and cleaning of the post-use plastics; however, product design that leads to easier on-site sorting would help increase recycling rates of these plastic fractions (Joseph et al., 2021). Current practice in the operating theatres at Næstved Hospital is to separate hazardous waste and sharps, and the remainder is treated as residual waste.

If it is not possible to switch products to reusable alternatives, there is great potential for sorting many of these plastics for recycling, specifically single-polymer products such as polypropylene (PP) bowls and trays as well as water and NaCl bottles. These considerations could drastically reduce the amount of single-use plastic waste generated.

Slagelse.

In addition to the urology and orthopaedic departments, observations were also conducted in the gynaecology and gastroenterology surgical departments at Slagelse Hospital. Amounts of products used per operation within these departments are depicted below.

The gynaecology department was the most observed department, with a total of 15 observations out of 31. Amounts for hard and small plastic products in this department remained relatively low compared to all other departments observed. This may be correlated to the associated tools used in these surgical procedures, which consisted mostly of reusable metal tools sanitized within the hospital's sterilization department. Additionally, the use of syringes and syringe caps, respectively, was lower than at other departments observed; this could also be attributed to the type of surgical procedure needed for these specific types of surgery. This shows that procedural use of single-use and reusable products differs between departments (and hospitals) and indicates a general potential for reducing plastic consumption by drawing from the experience at departments that have procedural use of reusable tools, such as the gynaecology department at Næstved hospital, to decrease the overall amounts of single-use plastic waste.

The gastroenterology department was the second most observed department with a total of 9 observations out of 31. Gastroenterology procedures often included endoscopy, a minimally invasive procedure where small-scale surgical instruments are inserted into small incisions made in the abdomen (Marescaux and Diana, 2015). These tools are typically either composite material or multi-polymer products, which make recycling potentials very limited. As mentioned previously, the product design phase of medical products should also consider the end-of-life phase to increase recycling potentials. Current product design of laparoscopic tools should include single-polymer considerations with detachable sharp portions to increase sorting and recycling potential after use.

Additionally, the gastroenterology department at Slagelse, Fig. 5, used the most composite packaging per operation, on average. This can also be due to the amount of individually wrapped products and tools associated with the procedures as well as the laparoscopic technique (see Fig. 6).

Both departments follow a similar pattern of product usage to the other surgical departments, with composite soft packaging, soft plastic and hard plastic categories being used the most. Like Næstved, current procedures at Slagelse require the separation of hazardous waste and sharps, with the remainder of the surgical waste treated as residual waste. There is great potential in these two departments at Slagelse for on-site sorting of single-polymer plastic products, such as syringes, as these seem to be most used in the gastroenterology department.

It becomes clear that the potential for sorting some of these multi-polymer and composite material products is less viable than single-polymer non-composite products (Joseph et al., 2021). To suit the surgical staff and the rigid procedural flows associated with surgery, on-site sorting should be made as simple and straightforward as possible. Therefore, product design should favour these recycling and sorting potentials in early phases of the product life cycle (Joseph et al., 2021). Additionally, careful consideration should be given to and observations made within each department of a hospital to get an overview of key products and processes and to think about using potential alternativee products and processes. This would help reduce plastic procurement and plastic waste generation within these healthcare facilities.

3.2. Total weight of products/packaging

Samples of products/packaging were individually weighed to assess the total weight of products and packaging per observation (Fig. 7). The weight of plastic products used per operation becomes relevant as a means of quantification as well as when considering the current climate crisis; incineration of 1 kg of medical waste can emit roughly 3 kg of CO_2 (Southorn et al., 2013).

The heaviest fractions of plastic waste are in the hard plastic (39%, 36%), soft plastic (18%, 22%), and blue sheet categories (20%, 33%) for

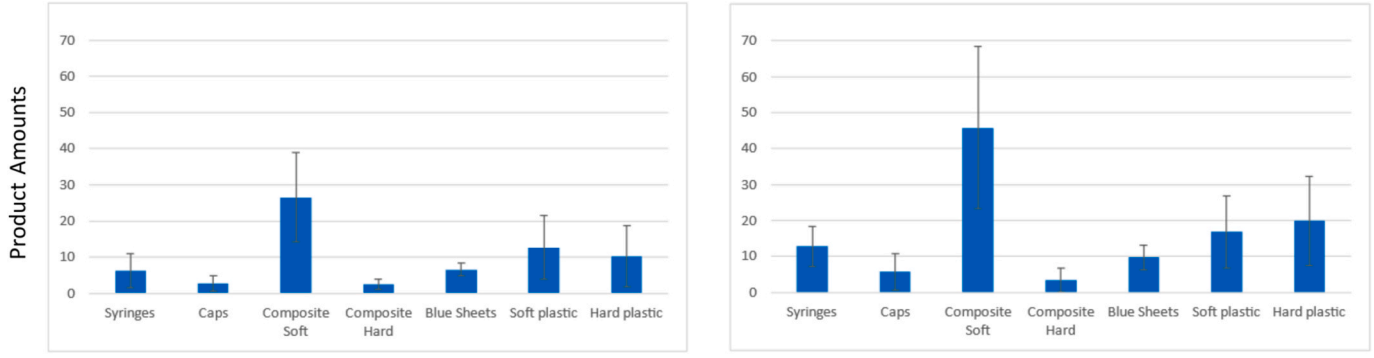


Fig. 5. Amounts of products per operation within the respective categories are illustrated. Within these departments, composite soft packaging remains the most prevalent, similarly to the other departments observed. The hard and soft plastic categories within both departments are the second most abundant categories. Additionally, syringe use seems to differ slightly between the two departments, with more syringes used in the gastroenterology department compared to the gynaecology department.

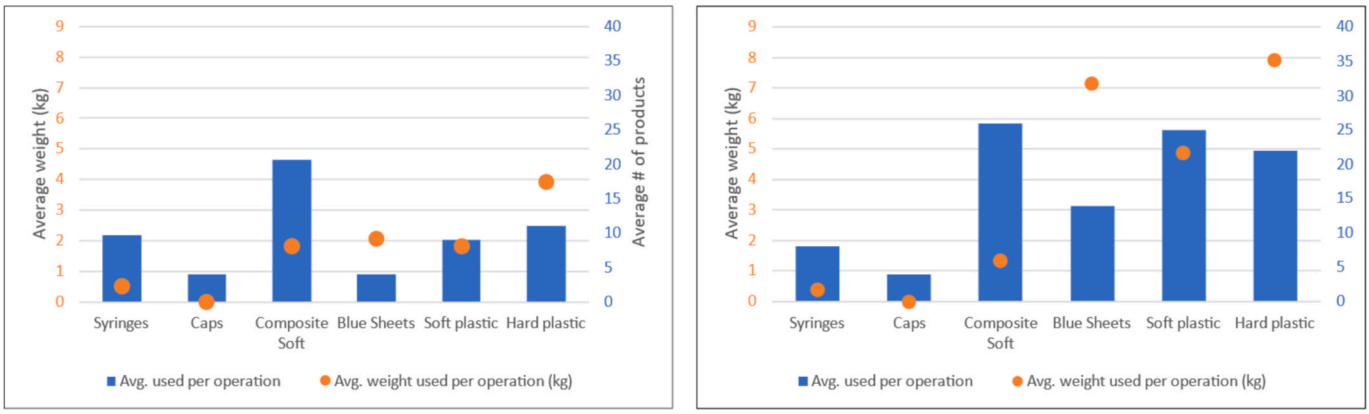


Fig. 6. The above graphs represent the average number of products used per operation (right axis and blue bars) compared with the average weight in kg used per operation (left axis and orange dots). The category 'composite hard packaging' was excluded as products samples were not easily accessible. This is because the composite hard packaging category often included surgical tools that were considered contaminated after use and therefore disposed of accordingly before being able to assess them. The average amount of products used per operation were used to calculate the average weight of products used per operation, within each respective category. As mentioned, and shown, the most common product used was composite soft packaging with averages of 21 and 26 used per operation in Slagelse and Næstved, respectively. The heaviest fraction of waste in Slagelse was within the hard plastic category with almost 4 kg used per operation. In Næstved, the heaviest fraction of waste was also the hard plastic category, with an average of almost 8 kg per operation.

Categories	Weight (kg) used per operation (average)		Weight (kg) per day used in Region Zealand		Average amount of CO_2 generated per day within Region Zealand
	Slagelse	Næstved	Slagelse	Næstved	
Syringes	0.492 kg	0.401 kg	18.2 kg	14.8 kg	99 kgs
Caps	0.0048 kg	0.0042 kg	0.18 kg	0.15 kg	1 kg
Composite packaging (soft)	1,082 kg	1,365 kg	40.0 kg	50.0 kg	270 kg
Blue sheets	2,071 kg	7,169 kg	76.6 kg	265.3 kg	1,026 kg
Soft plastic	1,810 kg	4,884 kg	67.0 kg	180.7 kg	743 kg
Hard plastic	3,916 kg	7,941 kg	144.9 kg	293.8 kg	1,316 kg

Fig. 7. Plastic product categories with respect to overall weights per category and per hospital. These values were used to project the average weight used (in kg) per day within all of Region Zealand. As mentioned, hard composite packaging, usually encasing composite material surgical tools from producers/manufacturers, were not included.

Slagelse and Næstved, respectively.

Due to the large sizes of the medical drapes and sterile coverings, compared to the other products/packaging, the 'blue sheet' category has been observed to take up the most space in the OT waste bins, and this was constantly seen throughout all departments. It was not uncommon to see up to four large waste bags being used per operation. These observations are in accordance with Albert and Rothkopf (2015), who estimated that blue wrap alone, used to encase sterile medical tools and usually made of non-woven polypropylene, makes up as much as 19% of operating theatre waste. With operating theatres producing a large proportion of total hospital waste, sterile blue wraps are thus a significant source of plastic waste in healthcare.

Within the region, on average, there were 37 operations performed per day within the relevant observed departments from 2019 to 2020. Using the ratio of consumed CO_2 per kilogram (Southorn et al., 2013), the total amount of CO_2 produced by the operating theatre per year can be estimated using equation (1).

Equation 1

X * 37 = Y Y * 3 = kg of C02	X = weight of products/packaging used per operation 37 = average number of operations in the region per day Y = weight per day used in the region

The 'blue sheet' category as well as the 'hard plastic' categories contain the heaviest fractions of waste. As mentioned above, sorting potentials for these single-polymer fractions of waste should be considered by both hospitals. Additionally, separate 'blue sheet' sorting could also reduce the number of times the waste bins in the OT are replaced, further reducing the amount of plastic waste and CO_2

generated.

3.3. Polymer analysis

The most common polymer types present were PP, PE, and PET but several others were represented, as shown. Most products and packaging include more than one polymer, some products such as nasal cannulas and IV tubes include up to five different polymers per product. Based upon the observations and supporting literature, it is found that even though most waste from the operating theatre is not contaminated (has had no contact with the patients) and therefore could be included in the general waste stream, it is typically treated as contaminated (Gamba et al., 2021).

3.4. Procedural flows and staff surveys

It is well known that staff have a major influence on the productiveness of potential implementations and should be directly involved in these initiatives by their willingness to incorporate more sustainable practices in their everyday procedures without hindering their quality of care (Beloeil and Albaladejo, 2021).

In the current study, workflows were observed with the help of in-depth field notes to assess considerations within the pre-operative phase, the operative phase, and lastly the post-operative phase. Procedural flows assessed in this manner provided insights into the specific flows/processes of each department and surgical team as well as into the specific points of waste generation.

The observations indicated that most plastic waste generation was created during the pre- and post-operative phases of surgery. Small fractions of waste were constantly disposed of, while larger fractions of waste were created when the nurses were preparing for the operation and unpacking the tools and products to be used. This was also the case in the post-operative phase, when the patient was no longer present and the cleaning/clearing of the operating theatre was done, mainly by nurses and to some extent the anaesthesiologists. Similarly to the nurses' workflows, anaesthesiologists also generated the most waste during the pre-operative phase; however, there was also some waste generation during operation as well as post operation, in cases where continuous administration of anaesthesia was needed. Interestingly, doctors themselves hardly handled plastic waste, as most of it was discarded post operation.

Workflow analyses and staff survey responses provide insights into potential practical limitations on the implementation of solutions that could otherwise reduce plastic consumption. When considering the current design of some medical products, it becomes evident why most medical plastic waste is not being recycled currently (Joseph et al., 2021). As already mentioned, several products are impossible to separate and discard/recycle properly or, when possible, the effort is too great for staff and therefore not continuously implemented. Feedback from staff in the current study revealed that one of the hospitals had experimented with a sorting system for recycling composite soft packaging. The experiment proved to be unsuccessful when staff realized that the effort required to separate the paper and plastic portions resulted in sore hands and fingers, implying a procedural and occupational hazard. In this current example, efforts should instead be placed on external producers and manufacturers, since what was needed to increase recycling rates was a change in product design. Other hindrances to plastic reduction efforts mentioned by staff in the surveys are the potential disturbance to workflows, lack of space for additional sorting options, and the need to ensure the sterility of medical tools. Potential solutions to these barriers also mentioned in these surveys were to reduce the amounts of single-use items being used, to use reusable items when possible and when sterility can be maintained, and to have more sorting options. Suggested implementations by staff align with the suggestions found in this study. This case illustrates the importance of working with a mixed method approach, where staff experience and quantification of material flows are combined when analysing potentials to reduce plastic products in the healthcare sector.

Additionally, it was observed that almost all the syringe waste generation came from anaesthesiologists' procedures at both hospitals. This is relevant since these products are mostly single-polymer products, suggesting that this product type is well suited for recycling if properly sorted.

3.5. Recommendations

As illustrated in the table (See Table 2), the four suggested implications span the production, use and end-of-life phase of observed plastic medical products and associated process/procedures. Current barriers to these implementations, as suggested, are the responsibility of producers, who should design medical products with the end-of-life phase being taken into account. Medical staff procedural flows should include the use, handling, and storage of multiple-use products to further facilitate the transition to more multiple-use products. In addition, current waste management of operating theatre waste does not include sorting any potentially clean and high-quality plastic products, and this should be the last phase of the considerations according to the waste hierarchy, but an important one nonetheless. Acting on these considerations, Region Zealand should expect to reduce the amount of single-use plastic waste being generated in operating theatres.

4. Conclusion

To conclude, there are often very high standards of sterility and quality control concerns which translate into surgical processes/procedures that involve mostly single-use disposable items in most medical facilities. Cross-contamination and on-site infection potentials steer procurement teams to justify procurement of plastic SUDs that are treated as residual waste after use. The continuation of this behaviour has led medical facilities to become leading sectors of environmental pollution and carbon emissions. If we are to envision a future where healthcare facilities focus on both the patient and the planet, we must consider implementations to suit the current processes/procedures that are being carried out.

Additionally, it is not plausible to consider the replacement of all single-use products currently being used by medical facilities; however, targeting a select few products or processes can have huge impacts on overall waste generation. For this reason, direct observations of medical departments and facilities can provide a great deal of insight into site-specific and product-specific implementations. Moreover, the inclusion of medical staff in the development of these implementations may lead to greater success, as it suggests a bottom-up approach, where key staff involved in handling these products/packaging are included because of this experience and also when considering recommendations that may alter their procedural flows.

Furthermore, it becomes pertinent to highlight and address the distinction between internal and external responsibilities. While staff have a very big influence on the use and sorting phases of products, it is up to manufacturers and producers of these medical products to reconsider current product designs to assist in facilitating better end-of-life options, as opposed to disposal. Current design of most medical products takes into account both patients and medical staff, but unfortunately excludes considerations for the planet. This research offers a proposal to external stakeholders to encourage the consideration and production of more single-polymer products designed with either reuse or recycling in mind. It also sets out a proposal for internal responsibility of the hospital in upholding these ends, such as by reducing the use of single-use products and sorting for recycling when applicable.

Author contribution

Tiffany Ramos: Conceptualization, Methodology, formal analysis,

data curation, writing- original draft, writing- review and editing, visualization. **Thomas Budde Christensen**: conceptualization, methodology, writing- review and editing, supervision. **Nikoline Bang Oturi**: writing- review and editing, visualization. **Kristian Syberg: conceptualization**: methodology, validation, writing- review and editing, supervision.

Funding

This research was partly funded by Region Zealand.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.135379.

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